Stratospheric ozone, ultraviolet radiation and climate change

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Introduction

Overexposure to ultraviolet (UV) radiation can lead to damage to the eyes and skin (WHO, 2006; Norval *et al.,* 2007). Skin cancer in particular is a major health concern. The three most common types of skin cancer are melanoma (the most dangerous but least frequent of the three), squamous cell carcinoma (which can develop quickly and deep in the skin), and the basal cell carcinoma (the least dangerous but most common). A skin condition known as actinic keratosis consists of pre-cancer lesions and has also been associated with UV radiation. The lesions are most often benign but can evolve into invasive squamous cell carcinoma. The prevalence rate of actinic keratosis is relatively large in the white population. This rate is estimated to be 15% in men and 6% in women in the United Kingdom (Memon *et al.,* 2000). Higher rates have been reported in the United States and Australia. It is difficult to quantify trends in the prevalence rate of skin cancer in the world but it appears this rate is increasing in many locations (de Gruijl *et al.,* 2003). There are multiple causes of this. Although UV radiation at the surface has increased over the last two decades, it is clear that human behaviours have changed over time, with an increase in sun-seeking holidays, outdoor leisure, changes in clothing, and an increase in the popularity of sunbathing, but also more risk awareness and utilization of protection measures (sun cream, clothes). Bentham and Aase (1996) showed positive correlations between skin cancer and income level in Norway in the 1960s and between skin cancer and foreign holidays in the 1980s. Moreover, a continuous increase in life expectancy contributes to an increase in the total amount of UV radiation received in a human lifetime and the risk of skin cancer. Reporting may also have improved. Because of these complex links, we focus here on how atmospheric composition and climate influence UV radiation at the surface.

UV radiation

Solar energy is essentially radiated in the UV, visible and near-infrared spectrum. Although UV radiation only represents a small fraction of the total solar radiation, it is important because of the high energy content of the photons in this spectral range. One can distinguish:

- **UV-C:** wavelengths ranging from 100 to 280nm[1]. UV-C is very energetic but it is all absorbed very high in the atmosphere and does not reach the Earth's surface.
- **UV-B:** wavelengths ranging from 280 to 315nm. The amount of UV-B received at the surface depends on the thickness of the stratospheric ozone layer but is modulated by cloudiness, tropospheric ozone and aerosols.
- **UV-A:** wavelengths ranging from 315 to 400nm. UV-A is hardly absorbed by ozone and the amount received depends essentially on cloudiness and the concentration of aerosols in the atmosphere.

The amount of UV-A and UV-B radiation received at the surface also depends on the elevation (the higher the more radiation), the sun elevation (which itself depends on the season and time of the day) and the reflectivity of the surface (reflective surfaces like snow or a rough sea can increase downward surface UV through multiple scattering). Finally, the quantity of UV radiation received by a surface depends on its orientation (Oppenrieder *et al.,* 2005) (Figure 1).

The shorter the wavelength, the more energetic the radiation and the more hazardous it is for human health. Figure 2 shows the action spectrum of UV-B and UV-A radiation for carcinoma according to de Gruijl *et al.* (2003). In first approximation, the action spectrum results from the superposition of two action spectra on the skin DNA. Radiation is most damaging between 280 and 300nm and its dangerousness decreases exponentially between 300 and 340nm. A unit UV dose at 300nm has the same effect as a 5000-unit dose at the 340nm wavelength. It is therefore important to weight UV radiation at the surface with an action spectrum in order to account for the relative importance of the wavelength range. One usually uses a typical action spectrum for this, called erythemal action spectrum. This is illustrated in Figure 3 which shows two UV spectra, F(λ), corresponding to two different ozone columns (348 and 250 Dobson

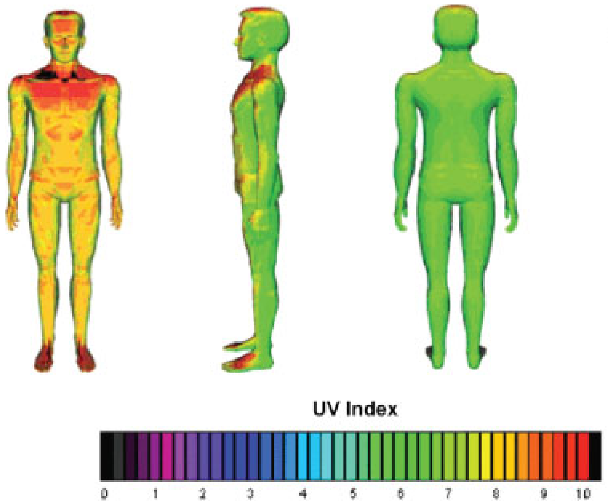

Figure 1. Exposure to UV radiation for a standing person facing south (solar azimuth angle 180.4°, solar elevation angle 65.7°). (From Oppenrieder et al.*, 2005. Reproduced with the permission of Meteorologische Zeitschrift; http://www.schweizerbart.de)*

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[1] The units of ultraviolet radiation are nanometres (nm): 1 nanometre is one billionth (10^{-9}) of a metre.

units)[2], weighted by the erythemal action spectrum, B(λ). Although the UV spectra hardly differ on the plot, they lead to weighted spectra that are very different between 290 and 320nm, because of the very strong wavelength dependence of the action spectrum. One can note the dominant role of UV-B, but it is clear as well that UV-A cannot be neglected. The erythemal function is defined as the integral over the UV spectrum of the surface radiation weighted by the erythemal action spectrum. Multiplied by an arbitrary number of 40, the erythemal function provides a UV index, which is convenient because it typically varies from 0 to 16, although larger values are possible in principle. The UV index does not exceed 8 in the United Kingdom (8 is rare and 7 may occur on exceptional days, mostly in the two weeks around the summer solstice). Indices of 9 and 10 are common in the Mediterranean area. A maximum length of solar exposure before sunburn can be defined for every UV index and skin type (Table 1).

Recent trends in UV radiation

Because of the strong wavelength dependence of the erythemal action spectrum, it is critical that the wavelength dependence of UV radiation be taken into account. Some radiometers have a spectral response similar to the erythemal action spectrum and can make a direct measure of the erythemal function. Some other instruments, known as spectroradiometers, can measure the spectral distribution of UV radiation but calibration of these instruments is complicated (Brogniez *et al.,* 2008). As a result there are few reliable long-term records of surface UV radiation covering several decades. For instance, broadband radiometers used in the United States since the 1970s proved not to have the stability required to detect UV trends (Tarasick *et al.,* 2003). A worldwide monitoring network – *Network for the Detection of Atmospheric Composition Change* – is now operational and already provides useful measurements to study the long-term evolution of surface UV radiation.

UV radiation can also be reconstructed from observations of the atmospheric composition. This is possible because radiative transfer theory is well-established and models can be used to estimate surface UV radiation. For instance we know relatively well how surface UV radiation varies with stratospheric ozone, which is the main parameter determining surface UV radiation in the absence of clouds. Figure 4 shows that every 1% reduction in stratospheric ozone column increases surface UV radiation by 1.1% in clear sky (Madronich *et al.,* 1998). This is critical in the context of stratospheric ozone depletion which has been observed in the Antarctic but also the Arctic polar region. Ozone depletion in the stratosphere is largely due to catalytic destruction cycles of ozone by atomic chlorine and bromine originating from the photodissociation of chlorofluorocarbon (CFC) compounds emitted at the surface.

As an example, the depletion of the stratospheric ozone layer observed on 10 October 2006 over Antarctica and off

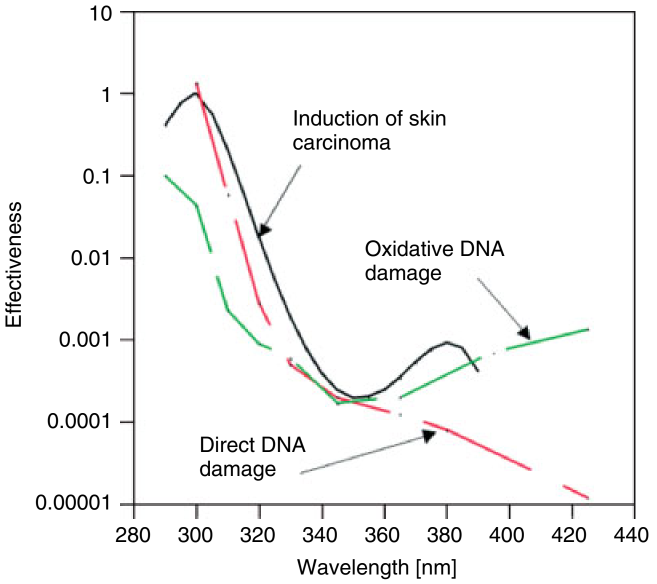

Figure 2. Action spectrum of the direct and indirect damage of UV radiation on DNA and squamous cell carcinoma (SCC). The three curves have been normalized to coincide around 350nm. The action spectrum on skin cancers corresponds to the total action spectrum of UV radiation on DNA damage (upper envelope of the green and red curves). (From de Gruijl et al., *2003. Reproduced by permission of The Royal Society of Chemistry (RSC) on behalf of the European Society for Photobiology and the European Photochemistry Association; http://dx.doi.org/10.1039/b211156j)*

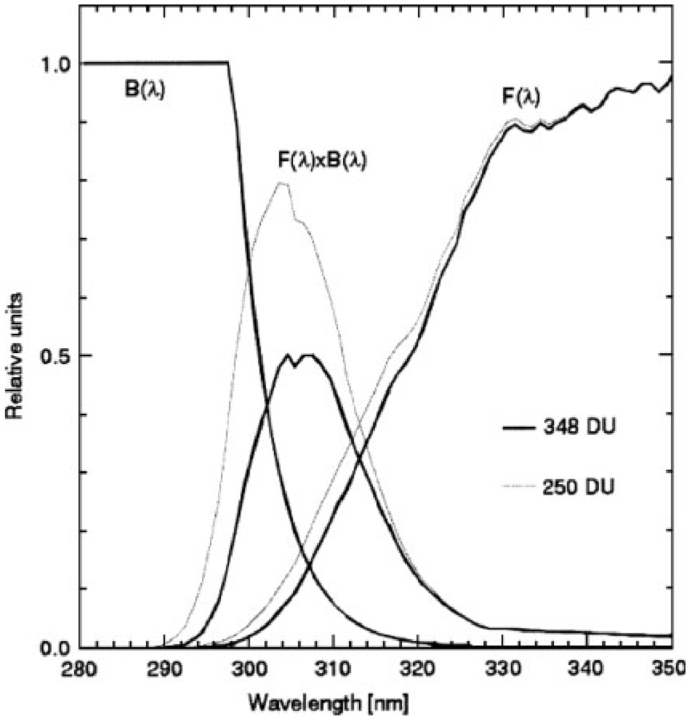

Figure 3. Spectral variation of UV radiation at the surface, F(λ), the erythemal action spectrum, B(λ), and the product of these two quantities for two different ozone columns (250 and 348 DU). (From Madronich et al., *1998. Reproduced with the permission of Elsevier.)*

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[2] The Dobson Unit (DU) is a unit used in atmospheric sciences to measure the vertical column of a trace gas in the atmosphere. 1DU corresponds to a thickness of 0.01mm for a gas under normal temperature and pressure conditions. An ozone layer of 300DU would therefore have a thickness of 3mm if it was taken to the Earth's surface.

Table 1

Sunpower number and maximum solar exposure before skin reddening for a UV index of 7 and for the four most sensitive skin types. According to www.eduspace.esa.int

Skin type	Indicative features	Sunpower number	Maximum exposure time for UV index of 7
1	Very light skin, often with freckles, reddish or light blond hair, blue eyes.	60	8 minutes
2	Light skin, fair hair, light eyes.	100	14 minutes
3	Light brown skin, dark-blond to brown hair, dark eyes (often).	200	28 minutes
4	Brown skin, dark hair and eyes,	300	42 minutes

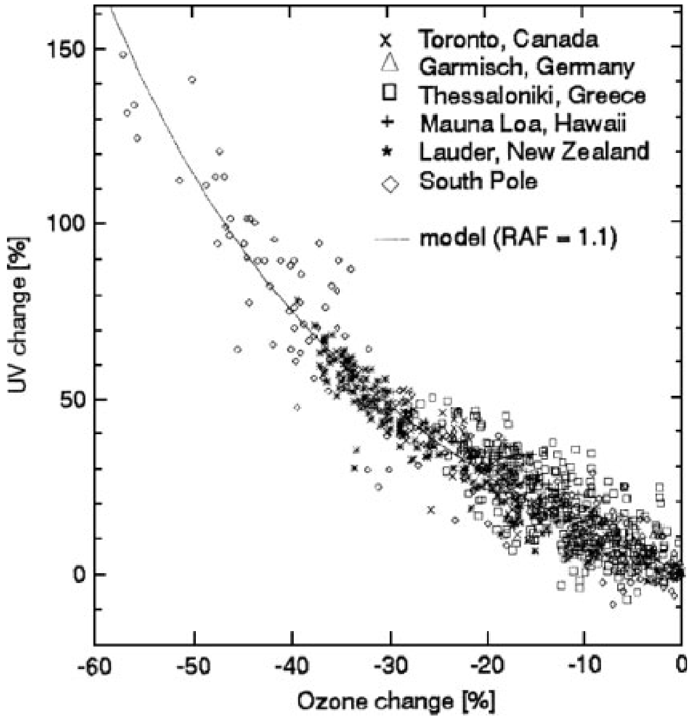

Figure 4. Relative increase (in %) of UV radiation at the surface (weighted by the erythemal spectrum) as a function of the change in the ozone column (in %) for several measurements sites. The thin solid line represented a fit to the observations which takes the form UV=(ozone)$^{-1.1}$. (From Madronich et al.*, 1998. Reproduced with the permission of Elsevier.)*

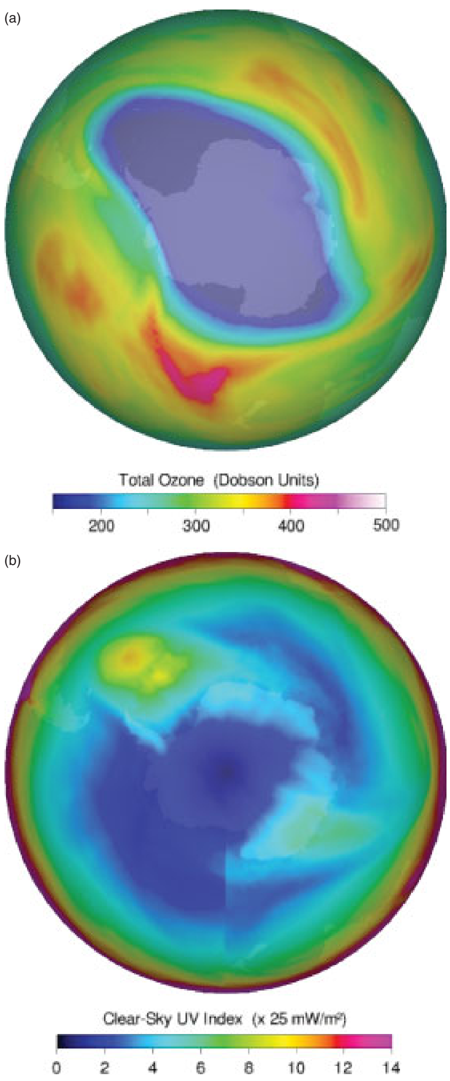

Figure 5. a) Ozone column (Dobson units) and b) clear-sky UV index in the Southern Hemisphere on 10 October 2006. (From http://www.temis.nl/protocols/o3hole/ Reproduced with the permission of KNMI/ESA.)

the southern tip of South America led to a significant increase in the clear-sky UV index with values above 10 off Patagonia (Figure 5). Only the northern part of the ozone-depleted region was associated with an increase in UV radiation because the South Pole region itself was just coming out of the polar night and was not receiving much light at that time of the year.

Madronich *et al.* (1998) have reconstructed the clear-sky UV index for different latitude bands in the two hemispheres for the period 1978 to 1994. The diminution of the ozone layer leads to an increase in UV radiation since the 1980s in mid- and high-latitudes that is particularly significant in the Southern Hemisphere. However, such reconstructions do not consider the effect of atmospheric aerosols and tend to overestimate surface UV radiation in polluted regions (Bais *et al.*, 2007).

It is more complex to reconstruct UV radiation in the presence of aerosols or clouds in the atmosphere. However, there are observations to calibrate and validate existing models. More elaborate reconstructions than the Madronich *et al.* (1998) study focused on particular sites. Kaurola *et al.* (2000) estimated surface UV radiation for Belsk in Poland, Norrköping in Sweden, and Jakloinen in Finland. Lindfors *et al.* (2003) recomputed UV radiation from measurements of ozone, sunshine duration and snow cover for Sodankylä in Finland. The same method was applied to observations in Davos, Switzerland, by Lindfors and Vuilleumier (2005). There is a clear increase in UV radiation during the last two decades of the twentieth century in northern Europe that is also observed in central Europe. At most sites the increase occurs only in spring when ozone destruction is at its maximum in the polar vortex, but at some sites one can also see an increase in UV radiation in the summer, as in Belsk, or in winter, as in Davos. It is likely that such increases are due to other reasons, like a change in cloudiness, rather than a thinning of the stratospheric ozone layer.

There are a few reliable datasets available that confirm the trends obtained from reconstructions at Belsk and Norrköping (Kaurola *et al.*, 2000). New Zealand has a high-quality dataset that shows an upward trend in surface UV radiation from direct measurements (Figure 6) (McKenzie *et al.*, 1999; Bais *et al.*, 2007). It is interesting to note that clear-sky UV indices are generally higher in the Southern Hemisphere as compared to the Northern Hemisphere for a given latitude. There are several reasons for this. In polar regions, levels of stratospheric ozone are less in the Southern Hemisphere because of the larger intensity of the polar vortex which cools the stratosphere and shifts the chemical equilibrium towards smaller concentrations. In particular, the formation of polar stratospheric clouds triggers the activation of chlorine species and fast catalytic cycles of ozone destruction. In mid-latitudes, ozone levels are more influenced by transport from the tropics that is less intense in the Southern Hemisphere. Moreover, the troposphere is cleaner there with less scattering and absorption by aerosols and trace gases (O_3, SO_2, NO_2). Finally, the Earth is closer to the Sun during the austral summer than during the boreal summer. This is why the thinning of the stratospheric ozone layer has led to an increase in clear-sky UV index in New Zealand from 10 in 1980 to 12 at the end of the twentieth century (McKenzie *et al.*, 1999).

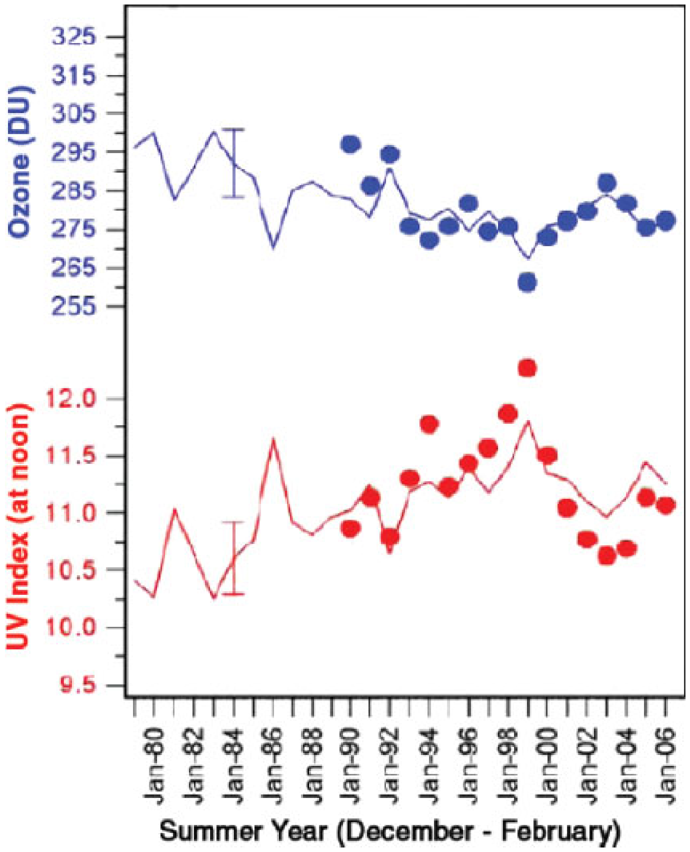

Figure 6. Temporal evolution of the ozone layer (Dobson units) and clear-sky UV index in New Zealand for summers of the period 1978/1979 to 2005/2006. The thin solid line represents the evolution of the ozone layer in summer (top) and a corresponding estimate of the UV index at noon (bottom). Filled circles represent actual UV measurements and retrieved ozone column from a spectroradiometer in the city of Lauder. (From McKenzie et al., *1999, updated by Bais* et al., *2007. © WMO.)*

How will UV amounts received at the surface change in the future?

It is clear that the observed increase in surface UV radiation in Europe is not sufficient to explain the increase in skin cancer occurrence. Behavioural changes, such as the increase in sun-seeking holidays, need to be considered as well. What about the future? To answer this question, we review the various parameters likely to impact UV radiation in Europe in the future. With the implementation of the Montreal Protocol and its Amendments the stratospheric ozone layer should eventually recover (Figure 7). How long this recovery to pre-1980 conditions will take depends on the region under consideration. It will be quicker in the Northern Hemisphere where recovery is expected as soon as 2050 than in the Southern Hemisphere where it may not happen until the end of the twenty-first century (Bodeker *et al.*, 2007). Stratospheric ozone and climate change interact strongly (Baldwin *et al.*, 2007). The cooling of the lower stratosphere due to increased greenhouse effect enhances the formation of polar stratospheric clouds. These clouds host ozone destruction mechanisms, which are very efficient in the presence of chlorine species and contribute to decreased ozone concentrations.

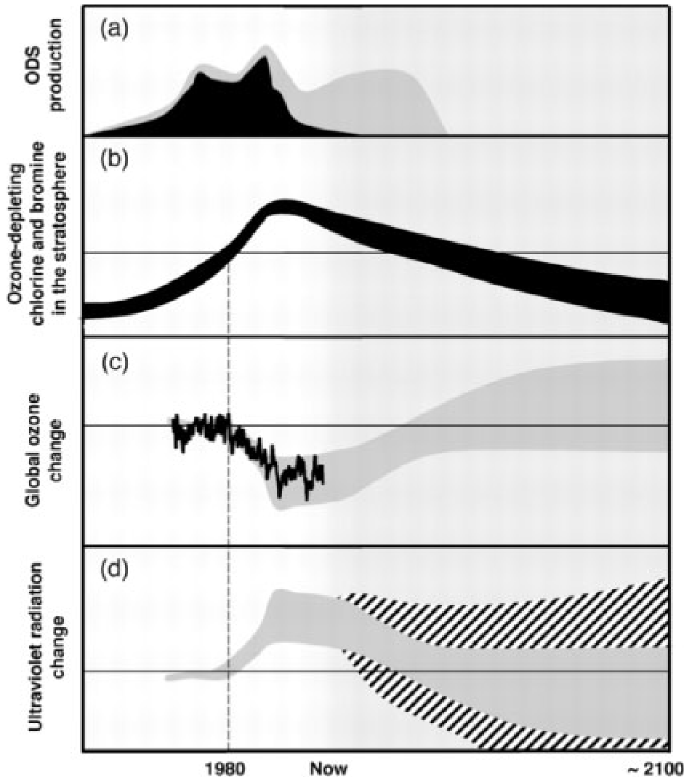

Figure 7. Past, and predicted evolution, of a) the production of ozone depleting substances, b) stratospheric concentration of chlorine and bromine species, c) the ozone layer and d) UV radiation at the surface. (From WMO, 2007. © WMO.)

This effect will persist longer in the polar vortex of the Southern Hemisphere as compared to the Northern Hemisphere. Altogether, climate change may contribute to an increase rather than a decrease in stratospheric ozone in some regions. Chemical reactions are temperature-dependent and cooling in the upper stratosphere decreases the ozone destruction rate by photochemistry, which contributes to increased ozone concentrations in that region of the atmosphere. Some models predict higher ozone column at mid-latitudes in the 2050s than in pre-1980 conditions. Beyond a simple effect of temperature on the chemistry, this increase is due to an acceleration of the Brewer-Dobson circulation. This is a slow meridional circulation, with an ascending branch in the Tropics and descending branches in the mid- and high-latitudes, which could increase in intensity with climate change (Butchart *et al.,* 2006).

Stratospheric ozone is the most important parameter that controls surface UV radiation because it is the only filter that is left when the sky is cloudless and the atmosphere is clean. However, a large part of the variability in surface UV is caused by variability in cloudiness, surface reflectivity and atmospheric aerosols (Arola *et al.,* 2003; Bais *et al.,* 2007). Beyond stratospheric ozone, other parameters will affect UV radiation in the future. It is likely that air quality control policies will continue to be strengthened and concentrations of tropospheric aerosols and ozone will decrease in the decades to come. The expected improvement in air quality will contribute to increased surface UV radiation. In some regions the snow cover will decrease, which may in contrast slightly decrease surface UV radiation, especially in springtime. The largest effect could come from the response of the hydrological cycle and clouds to climate change. This response is, however, very uncertain. Some models predict a significant decrease in precipitation and cloudiness over parts of Europe in summertime (UKCIP, 2002; Christensen *et al.,* 2007). Such a decrease in cloudiness would automatically lead to an increase in surface UV radiation. Longer summers and sunnier days would then change clothing behaviours and increase outdoors activities which would have more effect on UV exposure than any other factor (Bentham, 2008)!

Conclusions

Surface amounts of UV radiation have responded to past changes in stratospheric ozone, although the changes have been less – and more difficult to detect – in the Northern Hemisphere. The future evolution in UV radiation is governed by various factors that pull in different directions. The stratospheric ozone layer will eventually recover, thus resulting in a decrease in surface UV amounts, but air quality will hopefully continue to improve, leading to a small increase in surface UV amounts. Cloudiness may also respond to climate change in a way that could cause large changes in surface UV radiation. Estimates of the future evolution of the stratospheric ozone layer, cloudiness and surface UV radiation can be translated into projections of morbidity and mortality rates. However such estimates are inevitably very uncertain, as medical and sociological uncertainties add to the physical uncertainties discussed here. Information and communication to the public remain the best ways to limit the health impacts of an overexposure to UV radiation.

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More information

World Ozone and Ultraviolet Data Centre:
http://www.woudc.org/
Network for the Detection of Atmospheric Composition Change:
http://www.ndsc.ncep.noaa.gov/
World Health Organization:
http://www.who.int/uv/
Ozone secretariat of the UNEP:
http://ozone.unep.org/

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Letters

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An unusual observation of an electrical effect in thunderstorms

I was reminded of what follows in this letter while reviewing some of my activities when I was working in South Africa on a cloud physics field project. The events are recounted here because I have seen no similar accounts in the literature. Have any readers of *Weather* encountered a similar phenomenon?

We were a party of four (Graeme Mather, Carlota Mather, Charles Mather and myself) returning by car from the forest area above and to the west of the town of Nelspruit, in the late afternoon. We had no cameras with us. I can't remember the date or even the year, just that I was in South Africa during the summers (October through March) of 1983–1987. The sun was very low and at our backs as we were passing above the town and the paper-mill at Ngodwana when Charles drew our attention to cumulonimbus clouds of extraordinary vigour, accompanied by very strong electrical activity. We judged this to be located over the area known as Metaffin, east of Nelspruit, and opposite the sun. The observing situation was ideal: we, the sun and the clouds were almost on the same line, and the entire cloud area was illuminated by the parallel rays of the low sun.

The cloud towers were rising at astonishing rates, and appeared very 'hard' at their tops. The area seemed to be boiling. Lightning was very frequent, and several times channels emerged from the cloud tops and travelled down the cloud sides to the ground, something I had never seen before. On several clouds, near their tops, a fibrous, shiny, metallic, roughly cross-like pattern of striations (brighter than the brilliantly illuminated clouds themselves) appeared on the surface. After a few seconds the pattern would instantaneously change, and change again some seconds later, over and over.

We discussed this astonishing phenomenon and agreed that it had to be due to ice crystal orientation in the intense electrical fields at the surface of the clouds (Vonnegut, 1965; Foster and Hallett, 2002). The effects of crystal orientation in conjunction with cloud electrification have been reported in the literature (Hale, 1950; Ludlam, 1950), and also detected with sophisticated radar (Reinking *et al.,* 1997). Rapid, almost instantaneous changes in electrical field strength were reported above thunderstorms in conjunction with lightning flashes by Blakeslee *et al.* (1989). It surprised me to have to conclude that the outer surfaces of those cauliflower cumuli contained high concentrations of ice crystals. The fibrous appearance of the high reflectivity patterns suggests that the charge distributions causing the crystal orientations were similarly structured.

The sun was about to disappear behind the mountains behind us and we left in order to reach Nelspruit before dark. I have never again seen similar effects, although I've looked for them on many occasions. I swore to write the case up for a journal, but the pressure of our field programme favoured putting it off, until it was all but forgotten. Any comments or similar reports would be of great interest.

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